An Overview of the IXO Observatory

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ABSTRACT

The International X-ray Observatory (IXO) project is the result of a merger between the NASA Con-X and ESA/JAXA XEUS mission concepts. A facility-class mission, IXO will address the leading astrophysical questions in the "hot universe" through its breakthrough optics with 20 times more collecting area at 1 keV than any previous X-ray observatory, its 3 m^2 collecting area with 5 arcsec angular resolution will be achieved using a 20m focal length deployable optical bench. To reduce risk, two independent optics technologies are currently under development in the U.S. and in Europe. Focal plane instruments will deliver a 100-fold increase in effective area for high-resolution spectroscopy, deep spectral imaging over a wide field of view, unprecedented polarimetric sensitivity, microsecond spectroscopic timing, and high count rate capability. IXO covers the 0.1-40 keV energy range, complementing the capabilities of the next generation observatories, such as ALMA, LSST, JWST, and 30-m ground-based telescopes. These capabilities will enable studies of a broad range of scientific questions such as what happens close to a black hole, how supermassive black holes grow, how large scale structure forms, and what are the connections between these processes?

This paper presents an overview of the IXO mission science drivers, its optics and instrumental capabilities, the status of its technology development programs, and the mission implementation approach.

Keywords: X-ray, Observatory, IXO, Future Missions

1. INTRODUCTION

The extragalactic X-ray sky is dominated by two kinds of sources: accreting supermassive black holes (SMBH) in galactic nuclei, comparable in size to the Solar System, and clusters of galaxies, more than a million light years across. The energy liberated by growing black holes influences the infall of gas in galaxies and clusters, while some analogous process, still poorly understood, ties the growth of black hole mass to a fixed fraction of its host galaxy's bulge [1,2,3,4] The remarkable link between the two most populous types of extragalactic X-ray sources implies that a two-way connection called "feedback" is a key ingredient of understanding them both. The International X-ray Observatory (IXO), a joint NASA-ESA-JAXA effort, will address fundamental and timely questions in astrophysics: What happens close to a black hole? How did supermassive black holes grow? How does large scale structure form? What is the connection between these processes? Addressing these questions requires dramatic increases in collecting area combined with sensitive new instrumentation. Being an observatory class mission, IXO will also be able to address a large number of additional problems in contemporary astrophysics, such as: constraining dark energy; counting the missing baryons in the WHIM, the origin of cosmic rays in supernovae, studies of the interstellar medium, stellar mass loss and star and planet formation.

IXO's spectroscopic, timing, and polarimetric capabilities will probe close to the event horizon of super-massive black holes (SMBH) where strong gravity dominates. IXO will determine the evolution and origin of SMBH by measuring their spin to understand their merger history, surveying them to find their luminosity distribution out to high redshift (z~8), and spectroscopically characterizing their outflows during peak activity. IXO will revolutionize our understanding of galaxy clusters by mapping their bulk motions and turbulence. IXO will observe the process of cosmic feedback where black holes inject energy on galactic and intergalactic scales, and characterize the missing baryons in the cosmic web. Meanwhile, surveys of distant clusters will constrain cosmological models.

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IXO will have the ability to trace orbits close to the event horizon of black holes, measure black hole spin for several hundred active galactic nuclei (AGN), use spectroscopy to characterize outflows and the environment of AGN during their peak activity, search for super-massive black holes out to redshift z = 10, map bulk motions and turbulence in galaxy clusters, find the missing baryons in the cosmic web using background quasars, and observe the process of cosmic feedback where black holes inject energy on galactic and intergalactic scales. These achievements will be made possible by employing optics with 20 times more collecting area at 1 keV than any previous X-ray observatory. A suite of focal plane instruments will deliver a 100-fold increase in effective area for high-resolution spectroscopy, deep spectral imaging over a wide field of view, unprecedented polarimetric sensitivity, microsecond spectroscopic timing, and high count rate capability. The improvement of IXO relative to current X-ray missions is equivalent to a transition from the 200 inch Palomar telescope to a 22 m telescope while at the same time shifting from spectral band imaging to an integral field spectrograph.

The mission is on schedule for launch in 2021 to an L2 orbit, with a five-year lifetime and consumables for 10 years. As with previous major X-ray observatories, IXO will be available to the entire astronomical community. Previous experience assures us that unexpected discoveries will abound, and IXO will contribute to the understanding of new phenomena as they are uncovered — a key feature of all great observatories.

While this paper presents a necessarily brief overview of the mission, there are over 30 talks and posters in this conference containing a wealth of details about the IXO optics and instruments. Significantly more detail on all aspects the overall mission – its science, optics, instrumentation, spacecraft – can be found in the submissions to the Astro2010 Decadal Survey [5,6] as well as in many of the white papers submitted to the National Academy in support of the Decadal process.

2. IXO SCIENCE

One of the driving science goals of IXO is to understand evolution of black holes and the properties of their extreme environments, measure the energetics and dynamics of hot gas in large cosmic structures, and reveal the connections between these phenomena. IXO will also constrain the equation of state of neutron stars and track the dynamical and compositional evolution of interstellar and intergalactic matter. Despite our immediate focus on these topics, we note that IXO measurements of virtually every class of astronomical object will also return serendipitous discoveries, as with all major advances in astronomical capabilities.

Studies of Strong Gravity: The observational consequences of strong gravity can be seen close to the event horizon, where the extreme effects of General Relativity (GR) are evident in the form of gravitational redshift, light bending, and frame dragging. The spectral signatures needed to determine the physics of the accretion flow into the black hole are only found in X-rays. IXO will allow us to observe orbiting features from the innermost accretion disk where strong gravity effects dominate Observations of accretion flows around supermassive black holes (SMBH) can probe General Relativity's (GR) spacetime metric due to the geometric and dynamic simplicity of accretion disks. Each parcel of gas has an orbit around the black hole that closely approximates a circular test-particle orbit, with typical deviations less than 1% in such thin accretion disks [7]. IXO will add a new dimension—time—to the study of iron lines, with
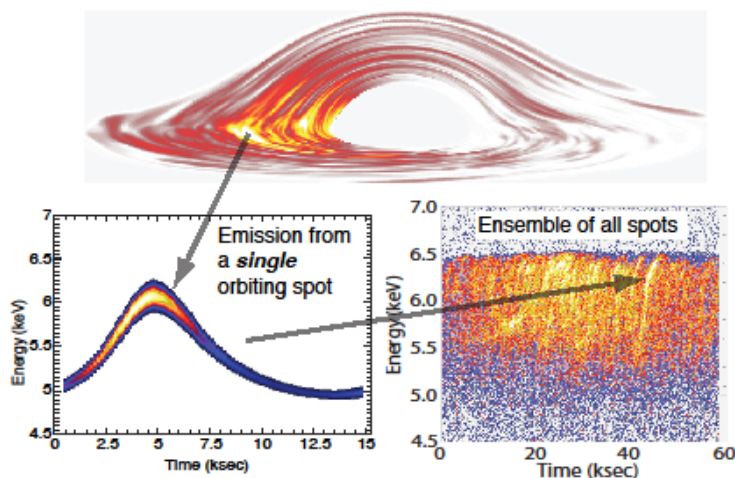

Figure 1: IXO will resolve multiple hot spots in energy and time as they orbit the SMBH, each of which traces the Kerr metric at a particular radius. In the time-energy plane, the emission from these hot spots appears as "arcs," each corresponding to an orbit of a given bright region.

"hot spots" of iron Ka emission in the disk appearing as "arcs" in a time-energy plane (Figure 1). GR predicts the form of these arcs, and the ensemble of arcs can be fitted for the mass and spin of the black hole and the inclination of the accretion disk. Deviations from the GR predictions will create apparent changes in these parameters as a function of time or hot spot radius.

The centroid of narrow but varying iron lines must be measured in at least 10 phase bins throughout the orbit (order of hours) for a range of SMBH masses. A mirror area of 0.65 m^2 at 6 keV will ensure at least 100 photons in the Fe line per orbital bin, enough for an accurate energy centroid, for about 10 SMBH targets. The X-ray Microcalorimeter Spectrometer (XMS) is the preferred instrument as it allows accurate centroiding of emission lines with ~100 photons and can detect other narrow features.

Measuring Black Hole Spin: Despite their immense potential for energy generation and consequent impact on cosmic evolution, black holes have only two measurable parameters: mass and spin. The spin of a SMBH depends upon its growth history: an accretion-dominated history leads to high spin and a merger-dominated one to low spin [8]; see Figure 2. The spin distribution of AGN is a powerful discriminator between growth histories of supermassive black holes that may otherwise form identical mass-functions. By determining the spins of a few hundred SMBH, using multiple approaches, IXO will determine how SMBH grow. The primary method is measurement of broad orbitally-averaged iron lines, which unlike the strong gravity study requires only moderate energy resolution (150 eV) but broad energy coverage to determine the continuum both below and above the 6.4 keV iron line. The combined Wide Field Imager/Hard X-ray Imager (WFI/HXI) will enable measurements covering 0.1–40 keV with adequate effective area and resolution at 30 keV from the HXI to measure the hard continuum.

Figure 2: RED – mergers of similar mass BHs. The spin is then determined by the last few mergers, which if pro-grade give high spin, but if retrograde or at 90degrees give lower spin. BLUE – accretion from a disk, which would typically spin in one direction, gives highest spin. GREEN – Growth via merging of many small BH, in this case the retrograde ones dominate because then have a larger ISCO and therefore accrete with higher angular momentum, but are retrograde, so drive spin to zero.

Another method determines spin by measuring the polarization properties of X-rays reflected from the disk, which depend upon the inner disk radius, a spin-dependent property [9, 10]. The expected polarization degree ranges from ~1-30%. Measuring this effect for ~10 SMBH leads to the requirement of 1% minimum detectable polarization (MDP) for a 1 mCrab source in 100 ksec. By comparison, the upcoming GEMS X-ray polarimetry SMEX would require 2.5 Msec to reach the same MDP for each source.

Growth of Supermassive Black Holes: SMBHs are a critical component in the formation and evolution of galaxies, and IXO can detect accretion power from embedded high-redshift SMBHs (10^7–10^9 solar masses), even when obscured [11] (see Figure 3). Luminous, ~10^9 M$_o$ SMBHs have been detected at z~6. Growing such massive SMBHs within the <1 Gyr requires sustained Eddington-limited accretion. Gas dynamical simulations predict a period of intense star formation and obscured accretion during the formation of these first galaxies, driven by a rapid sequence of mergers. IXO observations offer the most direct mmeans to discover and study accretion in these systems: IXO will determine the luminosity function of SMBHs out to z ~ 8, exploring the early growth phase of SMBHs.

This science can be achieved using a combination of large mirror effective area (3 m^2 at 1.25 keV), good angular resolution (5 arcsec) and large field of view (FOV; 18 arcmin diameter) with moderate spectral resolution ($\Delta E \sim 150$ eV @ 6 keV). These capabilities are provided by the WFI/HXI and will allow IXO to carry out a multi-tiered survey in a manageable amount of observing time (~10 Msec). IXO can efficiently survey significant areas of the sky an order of magnitude faster than Chandra and to a limiting depth that surpasses the 2 Msec Chandra deep field. The observational approach is a survey of increasing solid angle with decreasing exposure time (1000, 300, 100, 30, and 10 ksec, with solid angles increasing from 0.3 to 3.5 sq. degrees). This survey will need to be complemented by optical and IR surveys, so
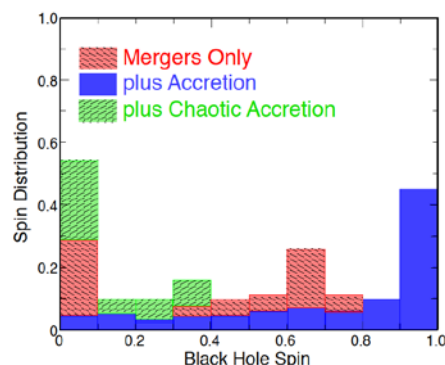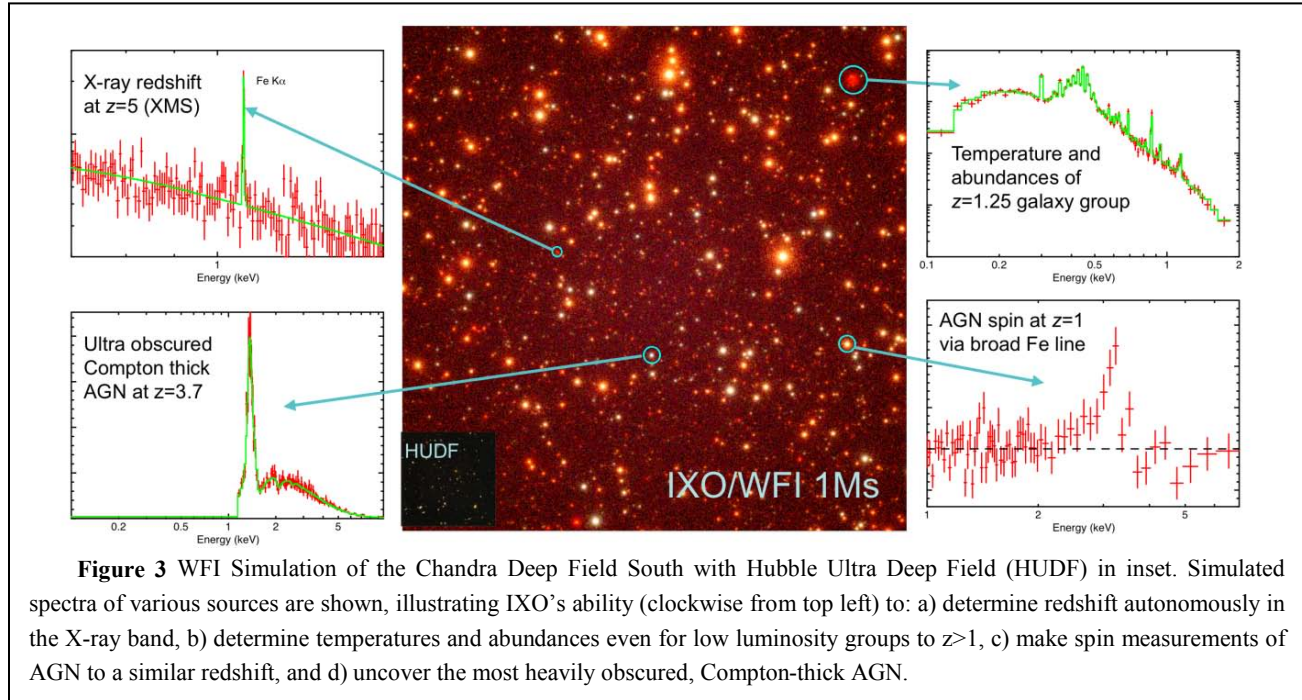
the point spread function (PSF) must be small enough that optical-IR counterparts can be identified. Combined with 5 arcsec resolution and a 50 photon source, the statistical error circle of the source centroid has a radius of 0.4 arcsec, which is smaller than the mean source separation even in the Hubble Ultra Deep Field (1.5 arcsec). Systematic errors on registration will be of a similar scale if at least three known sources are in the field to allow for post-observation astrometric correction (improving on the absolute astrometric accuracy from the attitude reconstruction of 1 arcsec). The IXO 0.5–2 keV confusion limit is ~6×10^{-18} erg/cm^2/s (PSF/5 arcsec), well-matched to the sensitivity of the 1 Msec survey component.

Figure 3 WFI Simulation of the Chandra Deep Field South with Hubble Ultra Deep Field (HUDF) in inset. Simulated spectra of various sources are shown, illustrating IXO's ability (clockwise from top left) to: a) determine redshift autonomously in the X-ray band, b) determine temperatures and abundances even for low luminosity groups to z>1, c) make spin measurements of AGN to a similar redshift, and d) uncover the most heavily obscured, Compton-thick AGN.

Neutron Star Equation of State: Neutron stars have the highest known matter densities in nature, utterly beyond the densities produced in terrestrial laboratories. At these densities, the uncertainties in the underlying physics lead to widely differing equations of state, each of which imply different neutron star radii as a function of mass. IXO will determine the equation of state for neutron stars via their mass-radius relationship for approximately a dozen neutron stars of various masses with several distinct methods [12]. The most robust method will measure energy dependent pulsations present during thermonuclear X-ray bursts from fast spinning neutron stars in low mass X-ray binaries (LMXB)[13]. The same modeling technique will allow mass–radius measurements for several rotation-powered millisecond X-ray pulsars [14]. Measuring the mass and radius of LMXB bursters requires fast relative timing (10 ms), high throughput (>105 cts/s), low dead-time and modest spectral resolution (150 eV). These capabilities are provided by the combination of IXO's large collecting area and the High Time Resolution Spectormeter (HTRS) detector. Modeling of simulated pulse profiles indicates that an ~8% measurement of mass and radius is statistically achievable using bright bursts which have pulsations present during burst rise. Another method uses the spectral resolution of the HTRS to detect rotationally-broadened absorption lines from these and other LMXB sources. This approach will provide an independent measure of the mass and radius, if the lines are sufficiently strong.

Evolution of Galaxy Clusters and Feedback: The extraordinary capabilities of IXO will reveal the major baryonic component of the Universe, in clusters, groups and the intergalactic medium (IGM), and the interplay between these hot baryons and the energetic processes responsible for cosmic feedback. IXO will open a new era in the study of galaxy clusters by directly mapping the gas bulk velocity field and turbulence. Galaxy formation depends on the physical and chemical properties of the intergalactic medium (IGM), which, in turn, is affected by energy and metal outflows from

galaxies (feedback). Detailed studies of the IGM in galaxy clusters are now limited to the nearby Universe (z < 0.5). IXO will measure the dynamical and thermodynamic properties as well as the metal content of the first low-mass clusters emerging at z ~ 2 and directly trace their evolution into today's massive clusters [16, 17]. High spectral resolution and sensitivity is needed to understand how the bulk kinetic energy of the gas is converted to heat. By mapping the gas velocities, IXO will reveal how the mechanical energy is spread and dissipated, wihle from accurate measurements of line profiles and from the variations of the line centroid over the image it is possible to deduce the characteristic spatial scales and the velocity amplitude of large (> kpc) turbulent eddies, while the total width of the line provides a measure of the total kinetic energy stored in the stochastic gas motions at all spatial scales.

Entropy evolution from the formation epoch onwards is the key to disentangling the various non-gravitational processes: cooling and heating via SMBH feedback and supernova-driven galactic winds. IXO will measure the gas entropy and metallicity of clusters to z ~ 2 to reveal whether the excess energy observed in present-day clusters was introduced early in the formation of the first halos or gradually over time, crucial input to our understanding of galaxy and star formation.

Measuring the evolution of the metal content and abundance pattern of the IGM with IXO will show when and how the metals are produced, in particular the relative contribution of Type Ia and core-collapse supernovae, and the stellar sources of carbon and nitrogen. Precise abundance profiles from IXO measurements will constrain how the metals produced in the galaxies are ejected and redistributed into the intra-cluster medium (Figure 4).

IXO's resolving power of 2400 at 6 keV (DE=2.5 eV, Dv=125 km/s) of the X-ray Microcalorimeter Spectromer (XMS) enables determination of the state of galaxy cluster evolution from velocity structures (including feedback from SMBHs), precise redshifts directly from X-ray observations, and allows turbulence to be measured in the intracluster medium. The resolving power also allows precise abundance measurements down to the photon-limited detection limit.

Cosmology: The growth of galaxy clusters, the largest virialized systems, is fundamental aspect of modern cosmology. In particular, the evolution of the mass function of galaxy clusters and a measurement of the distance-redshift relation [d(z)] places strong constraints on cosmology including the properties of Dark Energy. IXO observations of galaxy clusters will provide both tests, complementing other cosmological experiments [17].

Observations of 1000 clusters at z=1-2 together with existing low-z data will constrain the growth of structure independent of other methods. Precise temperature measurements and s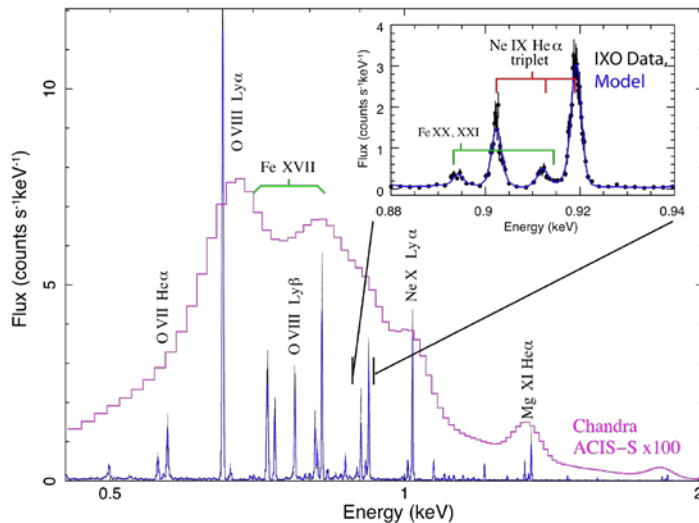urface brightness distributions are essential to determining the cluster masses, and in the outskirts of galaxy clusters these are done with the outer pixels of the XMS, with a resolving power of 150-300 in the redshifted Fe Ka line (10 eV @ 6 keV). A characteristic cluster diameter at 500 times the critical density (2R500) is 3 arcmin at z = 1 (5 keV cluster). Sky background near the galaxy cluster must also be measured, increasing the FOV to be observed. With the XMS, distant clusters will require only 1–4 pointings.

Figure 4: Simulation of a superwind from M82 as seen with a 100 ksec IXO observation. These high-resolution X-ray spectra (blue) show the metal-enriched hot gas outflowing from a starburst galaxy, a part of the feedback process unresolvable with current X-ray CCD data (magenta). IXO spectra will measure the velocity, abundances, densities, and ionization state of the wind, determining mass, metal and energy ejection rates.

Cosmic Web of Baryons: Less than 10% of the baryons in the local Universe lie in galaxies as stars or cold gas, with the remainder predicted to exist as a dilute gaseous filamentary network—the cosmic web. n addition to determining whether half the baryons in the Universe lie in the 0.3–10×10^6 K range, IXO will discover whether this hot gas is enriched by galactic superwinds (see Figure 4) and if it has the anticipated web-like topology. Superwinds are powered by massive star winds and by

core collapse supernovae which collectively create $T < 10^8$ K bubbles of metal-enriched plasma within star forming regions. These over-pressured bubbles expand, sweep up cooler ambient gas, and eventually blow out of the disk into the halo. While progress has been made in mapping cool entrained gas in outflows through UV/optical imaging and absorption line spectroscopy, it is the hot X-ray emitting phase of a superwind contains the majority of its energy and newly-synthesized metals. Knowledge of the chemical composition and velocity of the hot gas are crucial to assess the energy and chemical feedback from a starburst. These processes may be responsible for IGM enrichment and the galaxy mass-metallicity relationship.

For the missing baryons, key observations are the equivalent width measurements of He-like and H-like lines of O, N, and C, as seen against the continuum of bright background AGNs. The cosmic web should contain numerous O VII and O VIII absorption lines with equivalent widths of 2–8 mÅ [18]. These lines may have velocity structures imposed by galactic superwinds and the absorption may be associated with individual galaxies.

Addressing these two issues requires near-Doppler width resolving power, about R=3000 (v~100 km/s). This resolution is needed in the 0.3–1 keV range where the lines will occur, and it is achievable with the X-ray Grating Spectrometer (XGS). To determine the gas mass contribution, we need to define the differential equivalent width distribution for O VII, which will require about 200 absorption systems; ratios of other ions to O VII are valuable but needed for fewer cases. These goals can be met by measuring absorption lines toward 30 bright AGNs with 0.1 m^2 effective area for the XGS.

3. PERFORMANCE REQUIREMENTS

The key performance parameters for IXO have been developed from the science requirements as well as from a comprehensive science observing plan for the first year of operations that was developed using the White Papers submitted to the Astro2010 Decadal Survey. The science requirements have continued to be refined on the basis of new information obtained – primarily – from Chandra and XMM observations. Table 1 shows a subset of our key science performance parameters that are currently carried as our top level requirements. For each parameter, the associated science driver is shown. The IXO mission has been configured to achieve each of these performance parameters. Not shown are a number of top level mission requirements, such as observing efficiency (which in turn drives items such as required slew times, instrument changeover speeds, etc), the number of Targets of Opportunity per month, data latency requirements, etc.

Table 1 – Key Performance Parameters

Parameter	Value	Science Driver
Mirror Effective Area	2.5 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV	Black hole evolution, large scale structure, cosmic feedback, EOS Strong gravity, EOS Cosmic acceleration, strong gravity
Spectral Resolution/FOV E = 0.3 – 7 keV E = 0.3 –1 keV	ΔE = 2.5 eV within 2 arc min <10 eV within 5 arc min < 150 eV within 18 arc min E/ΔE = 3000 with an area of 1,000 cm^2	Black Hole evolution, Large scale structure Missing baryons
Mirror Angular Resolution	≤5 arc sec HPD <7 keV ≤30 arc sec HPD > 7 keV	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution
Count Rate	1 Crab with >90% throughput	Strong gravity, EOS
Polarimetry	1% MDP on 1 mCrab in 200 ksec (2 - 6 keV)	AGN geometry, strong gravity
Astrometry	1 arcsec at 3σ confidence	Black hole evolution
Absolute Timing	100 μsec	Neutron star studies

4. IXO OPTICS

The heart of the mission is the X-ray optical system.. A single mirror assembly with a ~3 m diameter and a 20 m focal length provides IXO's required 3 m^2 collecting area, and a deployable optical bench is employed to fit the optics and the science instruments within the launcher shroud. To reduce risk in achieving the required 5 arcsec angular resolution, two independent optics technologies are under development [19, 20, 21], one in Europe (the "Silicon Pore Optics") and one in the US (the "Segmented Glass Optics").

In the US, segmented glass technology has demonstrated ~15 arcsec performance with a path to achieve 5 arcsec and TRL 6 by early 2012. In Europe, silicon pore optics uses infrastructure from the microprocessor industry and has achieved ~15 arcsec with a path to reach 5 arcsec and TRL 6 by early 2012. The Flight Mirror Assembly (FMA) provides effective area of 3 m^2 at 1.25 keV, 0.65 m^2 at 6 keV, and 150 cm^2 at 30 keV. To meet the 5 arcsec mission-level half-power diameter (HPD) requirement for the observatory, the FMA angular resolution must be 4 arcsec or better. Attaining the large effective area within the launch vehicle mass constraint requires a mirror with a high area-to-mass ratio: 20 cm2/kg, 50 times larger than Chandra and eight times larger than XMM-Newton
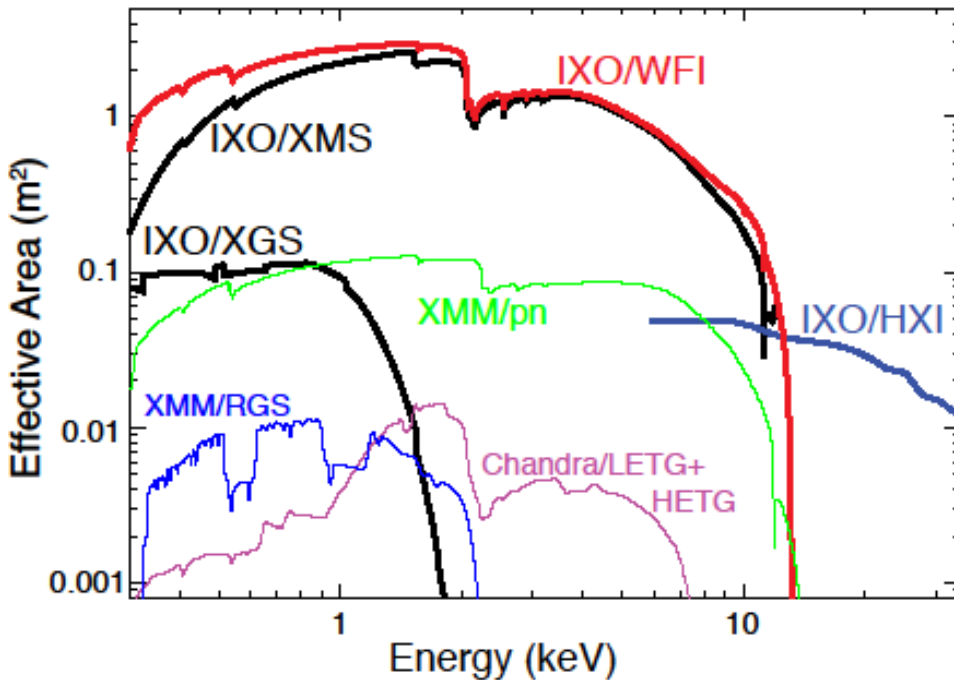

Figure 5: A comparison of the predicted effective area of the IXO optics/detectors with the current suite of in-orbit observatories. IXO will provide over 20 times the collecting area of any current mission,.and over 100 times the collecting area for high resolution spectroscopy.

5. IXO INSTRUMENTATION

The International X-ray Observatory has a strawman complement of five instruments. These are discussed in more detail in two overview papers in this conference [22, 23] as well as in instrument-specific talks (referenced below). Four instruments are mounted on a Moveable Instrument Platform (MIP) which are rotated into the mirror focus and operated one at a time for science data collection; and an X-ray Grating Spectrometer (XGS) that intercepts and disperses a fraction of the beam from the mirror onto a CCD (charge coupled device) camera, operating simultaneously with the

observing MIP instrument (see Fig. 6). The four MIP instruments are the X-ray Microcalorimeter Spectrometer (XMS) arrays (for high-resolution spectroscopic imaging),, an active pixel sensor Wide Field Imager/Hard X-ray Imager (WFI/HXI), a High Timing Resolution Spectrometer (HTRS), and a gas pixel imaging X-ray Polarimeter (XPOL). These instruments are currently at Technology Readiness Levels (TRL) 3–6, with plans to achieve TRL 6 by 2013.

The X-ray Microcalorimeter Spectrometer (XMS) [24] provides high spectral resolution, non-dispersive imaging spectroscopy over a broad energy range. The driving performance requirements are to provide spectral resolution of 2.5 eV over the central 2x2 arcmin in the 0.3-7.0 keV band, and 10 eV to the edge of the 5x5 arcmin field of view. The XMS is composed of an array of microcalorimeters, devices that convert individual incident X-ray photons into heat pulses and measure their energy via precise thermometry. The microcalorimeters are based on Transition-Edge Sensor (TES) thermometers. Currently, 2.3 eV spectral resolution has been demonstrated in a non-multiplexed TES and 2.9 eV has been achieved in a 2x8 array using a time-division SQUID multiplexer system. A Continuous Adiabatic Demagnetization Refrigerator (CADR) and a mechanical cryocooler provide cooling to 50 mK without expendable cryogens.

The Wide Field Imager / Hard X-ray Imager (WFI/HXI) are two detectors incorporated into one instrument [25, 26], with the HXI mounted directly behind the WFI. The WFI is an imaging X-ray spectrometer with an 18x18 arcmin field of view. It provides images and spectra in the 0.1-15 keV band, with nearly Fano-limited energy resolution (50 eV at 300 eV, <150 eV at 5.9 keV). The 1 arcsec pixel size oversamples the beam and thus minimizes pulse pile up. The WFI's key component is the DEPFET (Depleted P-channel Field Effect Transistor) Active Pixel Sensor (APS). Compared with earlier CCD-type detectors,
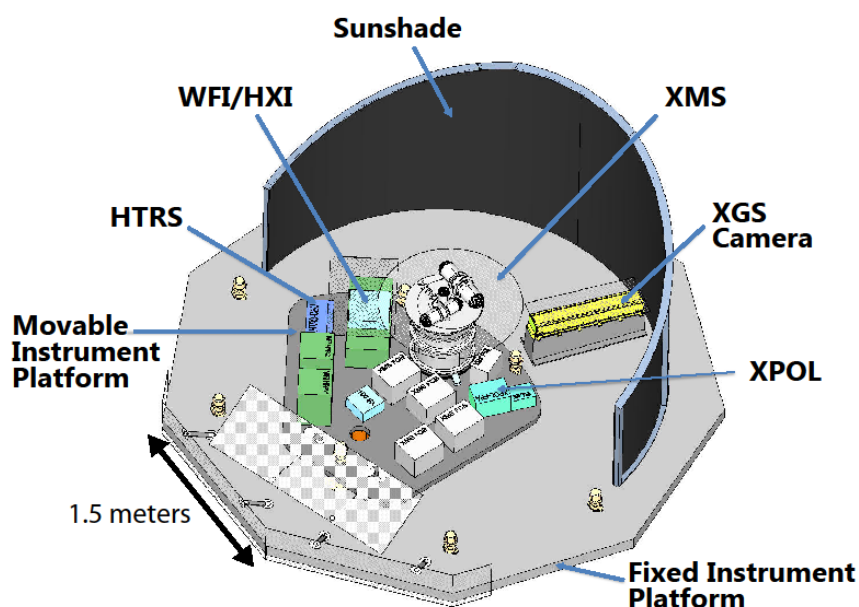

Figure 6: The IXO Instrument Module showing the Moveable Instrument Platform (MIP) that supports four of the instruments (XMS, WFI/HXI, HTRS and XPOL), while the read-out array for the gratings remains fixed and is always read out.

the APS concept has the significant advantage that the charge produced by an incident X-ray photon is stored in and read directly from each pixel, which reduces readout noise, and offers radiation hardness. Prototype DEPFET devices of 64x64 pixels have been tested successfully; an energy resolution at 5.9 keV of 126 eV has been demonstrated. The HXI extends IXO's energy coverage to 40 keV with an energy resolution ~1 keV (FWHM) at 30 keV and a FOV of 12x12 arcmin. The HXI is a 7x7 cm wide Double-sided Strip Cadmium Telluride (DS-CdTe) detector, based on those to be flown on ASTRO-H. It has nearly 100% detection efficiency up to 40 keV. The HXI will have energy resolution better than 1 keV (FWHM) at 30 keV and a FOV of 8 × 8 arcmin. To suppress background, five sides of the imager are surrounded by an active anticoincidence shield consisting of Bismuth Germanate (BGO) crystals viewed by Avalanche Photodiodes (APDs). In addition, two layers of Double-sided Silicon Strip Detector (DSSD) are mounted above the CdTe to serve as particle background detectors and detectors of 7-30 keV X-rays

The X-ray Grating Spectrometer (XGS) is a wavelength-dispersive spectrometer for high-resolution spectroscopy, offering spectral resolution ($\lambda/\Delta\lambda$) of 3000 (FWHM) and effective area of 1000 cm^2 across the 0.3-1.0 keV band. The arrays of gratings intercept a portion of the converging FMA beam and disperse the X-rays onto a CCD array. Two viable grating technologies reduce risk: one utilizes Critical Angle Transmission (CAT) gratings [27] with heritage from the Chandra High Energy Transmission Grating, but substantially higher efficiency. Another approach uses ``off

plane" reflection gratings [28] based on XMM-Newton gratings. To give higher performance the IXO gratings are ruled along the direction of incidence rather than perpendicular to it as on XMM-Newton.
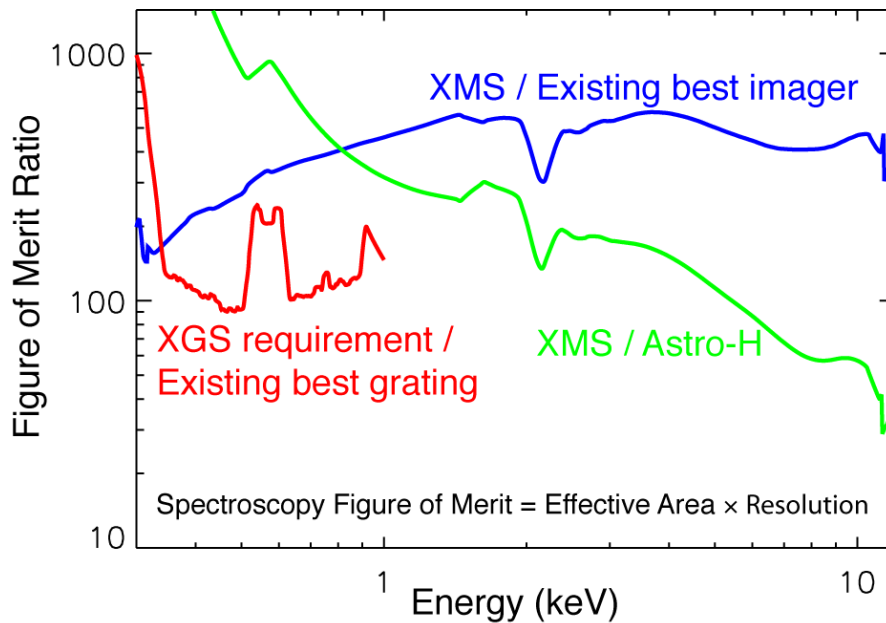

Figure 7: The figure of merit for improvement in high resolution X-ray spectroscopy is the product of the effective area times the resolution at each energy. This figure shows the ratio of IXO's XMS and XGS instrument performance relative to the best existing imagers and gratings currently operating (XMM imager and Chandra gratings) or planned for the near-future (the Astro-H calorimeter). Note the factors of several hundred improvements over most of the IXO bandpass.

The High Time Resolution Spectrometer (HTRS) [29] will perform precise timing measurements of bright X-ray sources. It can observe sources with fluxes of 10^6 counts per second in the 0.3–10 keV band without performance degradation, while providing moderate spectral resolution (~200 eV FWHM at 6 keV). The HTRS is an array of 37 hexagonal Silicon Drift Diodes (SDD), placed out of focus so that the converging beam from the FMA is distributed over the whole array. The key HTRS performance requirement has been demonstrated using existing detectors and standard analog readout electronics.

The X-ray Polarimeter (XPOL) XPOL utilizes a fine grid Gas Pixel Detector to image the tracks of photoelectrons produced by incident X-rays, which convey information about the polarization. is an imaging polarimeter, with polarization sensitivity of 1% for a source with 2–6 keV flux of 5×10^{-12} ergs cm^{-2} s^{-1} (1mCrab). XPOL utilizes a fine grid Gas Pixel Detector to image the tracks of photoelectrons produced by incident X-rays and determine the direction of the primary photoelectron, which conveys information about the polarization of the incoming radiation. The key XPOL performance requirements have been met in the laboratory, and a prototype detector has been vibration and thermal vacuum tested.

6. MISSION ARCHITECTURE

All mission requirements were flowed down from the science objectives, the measurement requirements, and the payload accommodation and performance requirements. The International X-ray Observatory (IXO) will be placed via direct insertion into an 800,000 km semi-major axis 180 day halo orbit (Figure 8) around the Sun-Earth L2 libration point (essentially identical to the JWST orbit) using either an Evolved Expendable Launch Vehicle (EELV) or Ariane V launch vehicle; the deployment module allows the observatory to fit into either launch vehicle fairing.

IXO is a Class B mission, which means there can be no performance degradation from a single point failure. The
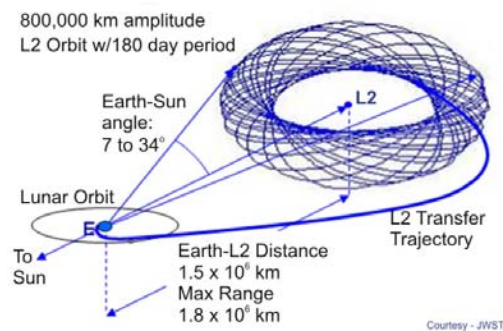

Figure 8: The IXO Orbit

mission design life is five years, with consumables sized for 10 years. The L2 orbit facilitates high observational efficiency and provides a stable thermal environment The allowed attitude relative to the sun line is 70°–110° (pitch), ±180° (yaw); ±20° (roll) defines the available field of regard (Figure 9). These ranges keep detectors and radiators out of the sun while providing full illumination to the solar arrays throughout the mission. The space craft pointing requirement is 10 arcsec (3s), with post-facto aspect reconstruction accuracy of 1 arcsec; integrated modeling shows these accuracies are achievable with > 50% margin. IXO carries out observations by pointing at celestial objects for durations of 10^3–10^5 sec. Since all the detectors are photon counting, longer integrations can be performed by multiple exposures.
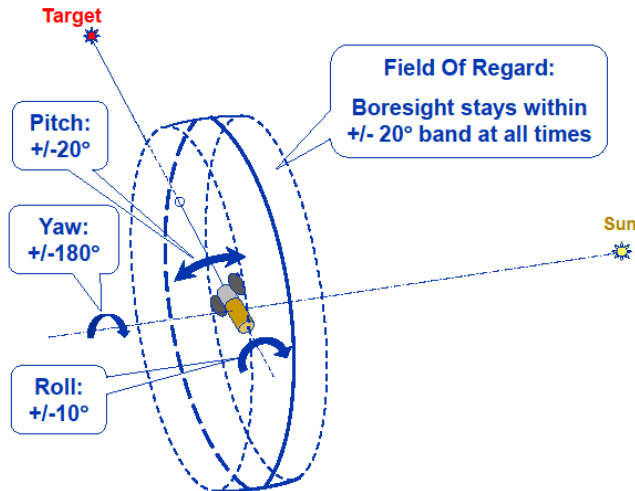

Figure 9: The IXO Field of Regard

NASA and ESA have each developed detailed spacecraft concepts that are remarkably similar in overall architecture. As required by the initial agreements to merge the Con-X and XEUS missions, both concepts are compatible with an EELV and Ariane V. Both studies concluded that the IXO spacecraft could be built with technologies that are fully mature today. All subsystems utilize established hardware with substantial flight heritage, and most components are "off-the-shelf. Figure 10 shows a layout for the NASA concept, and the relationship between the modules.

In both the NASA (described here) and ESA concepts [22], the IXO architecture consists of consists of four major modules (Instrument, Deployment, Spacecraft, and Optics; see Fig 10) that provide well-defined interfaces to simplify development and I&T, as well as facilitating shared development between international partners. This architecture facilitates parallel development and integration and test.

The Instrument Module (IM) (shown in more detail in Fig 6) accommodates the instruments. All detectors except the XGS camera mount to the movable instrument platform (MIP), which is comparable to moving platforms on

Figure 10: The observatory layout (NASA concept) that shows the relationship between the four primary modules.

Chandra and ROSAT. Focus and translation mechanisms, coupled with a metering structure metrology system based on Chandra heritage, assure centering of the detectors in the converging X-ray beam and accurate attitude reconstruction.
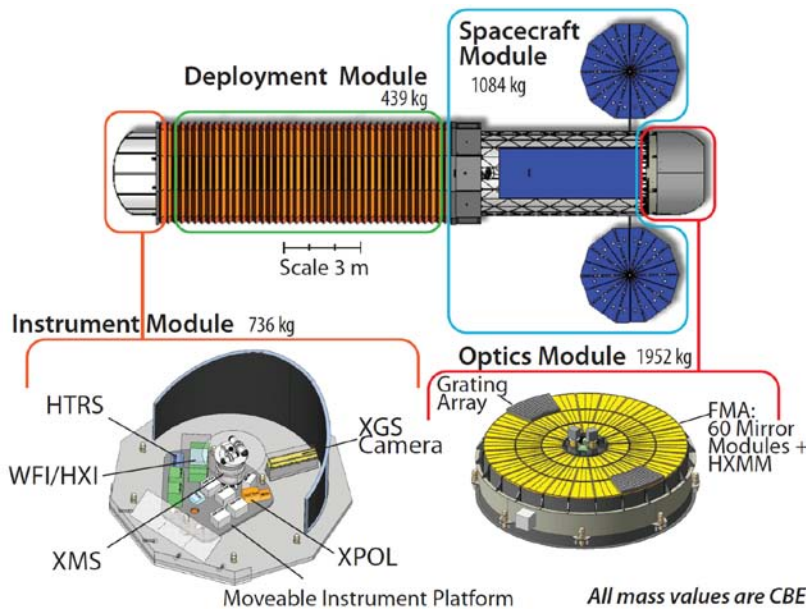
The Deployment Module (DM) is the portion of the metering structure which is extended on orbit. It consists of three identical ADAM masts, similar to those on NuSTAR. High precision deployment accuracy/repeatability was proven with the 60 m ADAM used in space on the NASA's Shuttle Radar Topography Mission. As the masts deploy, they pull with them wire harnesses and two pleated shrouds that shield the instruments thermally and from stray light. The shroud is structured as a Whipple Shield

(MLI thin foil layers spaced at specific distances) to minimize the number of micrometeroid penetrations.

The Spacecraft Module (SM) accommodates the bulk of the spacecraft subsystems including the power; propulsion; RF communications; guidance, navigation, and control; and avionics. The electronics boxes, reaction wheels, and propulsion tanks mount to a nine-sided honeycomb deck. The 6.6 m × 3.3 m diameter cylindrical composite metering structure accommodates the solar arrays, thrusters, and high-gain antenna.

The Optics Module (OM) includes the FMA, its sunshade, and the star trackers. The Optics Module interfaces the FMA to the fixed metering structure within the SM. The OM includes the FMA and its covers, the XGS gratings, the star tracker and telescope alignment periscope assembly, and the deployable sunshade. The Optics Module interfaces to the FMS at one end, and to the Launch Vehicle through the separation system at the other.

7. MISSION OPERATIONS

Mission operations will be conducted from the IXO Science and Operations Center (ISOC) that will provide the command and control, mission planning, and the science processing, archive, and user support functions for the mission The orbit at L2 is chosen for high target visibility and ensures no Earth and has occasional low obscuration (<14%) lunar penumbral shadows, simplifying thermal and power management. Primarily because of the orbit, the resulting observing efficiency (with a requirement for 85%) is higher than any previous X-ray observatory (~70% Chandra, ~60% XMM). The baseline concept for operations allows for spacecraft contact once per day for 30 minutes to perform a health and safety check and dump recorded telemetry. Command loads for future observations will be uplinked as needed (~once per week).

The observing schedule and subsequent pointing profile for IXO is expected to be similar to Chandra (or XMM) with ~1,000 maneuvers per year (~3 times per day on average in the early years, and decreasing over time as typical observation durations increase) to observe an average of ~800 science targets per year, reaction wheel unloading burns as required (~1–2 per week), and orbit station-keeping burns ~3 weeks apart (performed during slews). Wheel unloads and station-keeping burns are performed during real-time contacts. Based on the field of regard (Figure 9), the mission planning flexibility will be comparable with XMM-Newton and slightly less than Chandra. IXO will, however, have an increased efficiency due to the absence of radiation belt transitions. A limited number of Target of Opportunity requests are expected, and are planned for: currently, mission planning assumes that there will be up to two TOOs per month. Response time for a TOO is planned to be less than 24 hours.

8. ACKNOWLEDGEMENTS

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